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Hydrology and nutrient flux in an agrarian watershed of the Sikkim Himalaya

S.C. Rai and E. Sharma

Interpretive summary

A hydrological study was carried out in an agrarian watershed to determine erosion and runoff related to different land-use areas. Natural forest and agroforestry were determined to be the land uses most conducive to soil conservation.

Key words: agroforestry, Himalayas, land-use, watershed management.

ABSTRACT: A hydrological study was carried out in an agrarian watershed located in the Sikkim Himalaya. The Mamlay watershed has an elevational range of 300-2650 m above msl, with a total area of 3014 ha. The drainage of the watershed is dendritic type and the stream texture is fine on the higher elevation that gradually becomes coarse at the valley. The discharge was greatest in rainy season and smallest in summer. Sediment concentration of 325 mg/l was recorded during rainy season at the watershed outlet. Overland flow was greatest in open agricultural (cropped) area (9.6% of the precipitation) and smallest in cardamom agroforestry (2.17%). Soil loss of 477 kg/ha was recorded in open agricultural area, while it was very low (6 kg/ha) in dense mixed temperate natural forest. Large quantities of nutrients were lost through soil erosion from the open agricultural area in comparison to agroforestry systems. Agroforestry systems should be promoted in most of the areas where open agricultural practices are followed. The overland flow, soil and nutrient loss, and precipitation partitioning in different pathways in natural forest and agroforestry systems suggests that these land uses promote conservation of soil, water, and nutrients.

The watershed management approach is inherent to the objective of achieving a balanced development of diverse subsistence needs of people in an integrated manner rather than sectoral perspective (Sharma et al. 1992). The goal of watershed management is thus the rational utilization of land and water resources for optimal production with minimal disturbance to natural resources (Sundriyal et al. 1994c). The watershed management essentially relates to soil and water conservation by proper land use, protecting deterioration of soil, increasing and maintaining soil fertility, reducing soil erosion, conserving water for drinking and other farm uses, increasing the availability of basic resources and achieving the opti-

G.B. Pant Institute of Himalayan Environment and Development, Sikkim Unit, P.O. Tadong, Gangtok, Sikkim-737 102, India.

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mum productivity of land-uses (Sharma et al. 1992); Rai et al. (1994) have described the traditional conservation practices and relationships with land-use in Mamlay watershed in the Sikkim Himalaya. It was observed that the agricultural land area has considerably increased over the past 40 years (Sharma et al. 1992; Rai et al. 1994). The soil without tree cover on steep upland farming systems such as associated with more intensive agricultural practices is vulnerable to soil erosion and reduced soil fertility (Rai and Sharma 1995).

Information on the hydrological cycle in the hills is very important for considering management strategies at a watershed level. Unfortunately, there is no such data available for the Himalaya. The present investigation was undertaken to understand the different ecological processes involving hydrology in a hill watershed. The study was divided to consider the following (i) drainage, discharge, and sediment concentration, (ii) precipitation, overland flow, and soil loss in different land uses, and (iii) precipitation partitioning pathways in forests and agroforestry systems. The area of the study falls in the eastern Himalayan region that receives high rainfall. In recent years exponential growth in population and fragmentation of farm families have caused a reduction in landholding size, consequently forcing the farmers towards intensive cultivation (Rai and Sharma 1995). These above mentioned factors lead to enhanced soil and nutrient loss. This study broadly focuses on the above mentioned three hydrological aspects in considerable detail for different land uses and watershed as a whole, which could be useful in development and management planning.

Study sites

The Mamlay watershed is agrarian and located in the south district of Sikkim (27°10′ 8″ to 27°14′16″ N and 88° 19′53″ to 88° 24′ 43″ E) . It has an elevation of 300 to 2650 m above msl, with a total area of 30.14 km² encompassing 34 villages. There are 5 perennial streams (Tirikhola, Rangrangkhola, Poolkhola, Pokcheykhola and Chemcheykhola) which merge into Rinjikhola. Major land-uses in the watershed are temperate natural forest, sub-tropical natural forest, cardamom based agroforestry, mandarin based agroforestry, cropped area, fallow land and waste land. The micro-catchment for each perennial stream has a mosaic distribution of land-use practices. The watershed has 45% area in agriculture, 26% in forest and 29% in waste land as recorded using remote sensing techniques.

The watershed area lies entirely in the mountainous zone. The area is typified by folded structure and varied lithology with older rocks occupying the upper structural levels. It bears evidence of two persistent thrusts, the Sikkip and the Tendong. The major rock formations in the watershed are Damuda and Daling. The topography progressively becomes rugged from the Rangit river (west) to the Tendong peak (east) (Figure 1; Sharma et al. 1992).

Forestry in the watershed is broadly categorized into two types: (i) temperate natural forest (765 ha) and (ii) subtropical natural forest (21 ha). A total of 113 tree species have been recorded in the above forests of the watershed which indicates high biodiversity. Details on structure and functioning of these forests are provided by Sundriyal et al. (1994a) and Sundriyal and Sharma (1996). The upland farming system in the watershed presents good traditional agroforestry broadly divided into the large cardamom, mandarin and tree fodder based systems. Details on various aspects of farming systems of the watershed are provided by Sundriyal et al. (1994b) and on cardamom and mandarin agroforestry by Sharma et al. (1994 and 1995). Large cardamom (*Amomum subulatum*) and mandarin (*Citrus reticulata*)

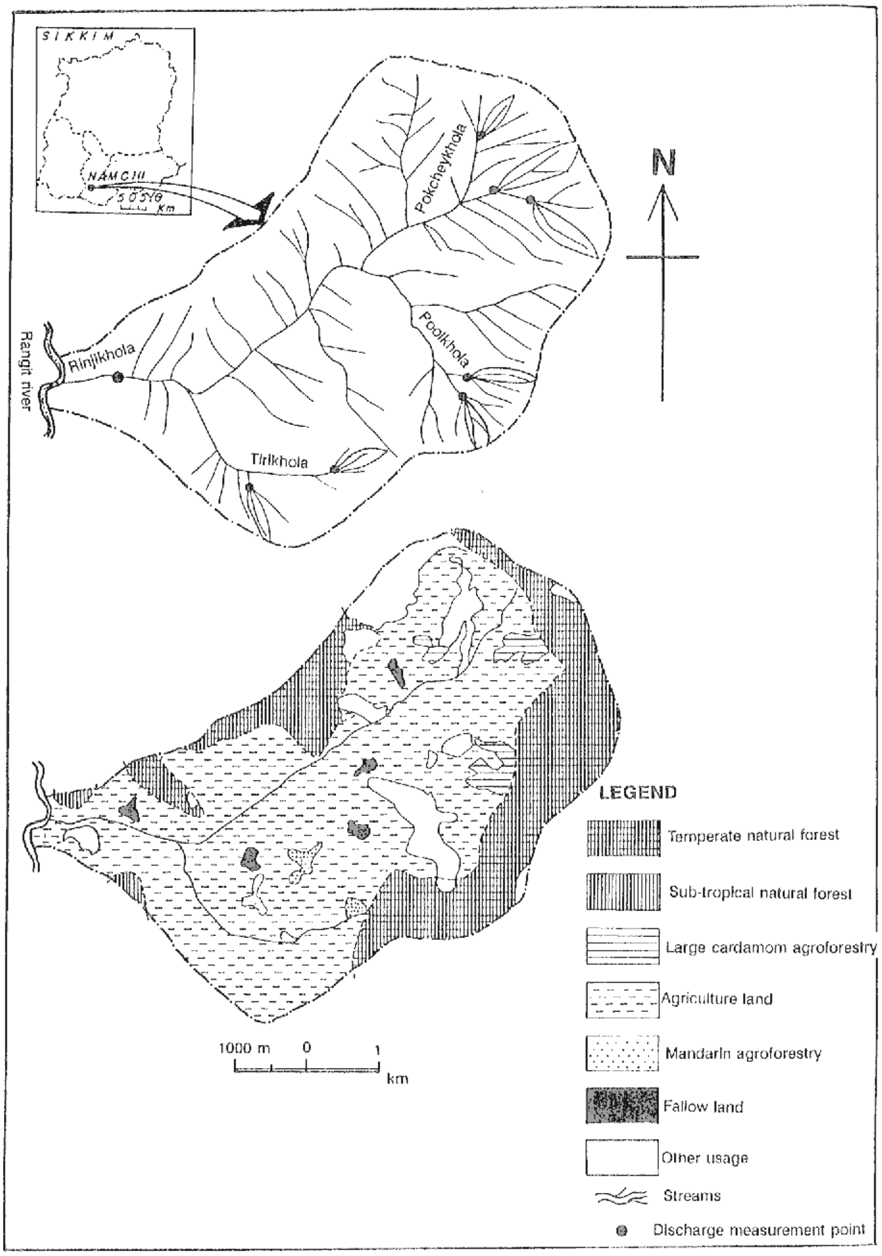

Figure 1. Location map of the Mamlay watershed in Sikkim Himalaya showing drainage, raingauge stations with altitude and land-use/land cover

Table 1. Site characteristics of stands selected for hydrological study in the Mamlay watershed

Site/Land-use	Altitude (m)	Slope (°)	Soil texture	Tree height (m)	Basal area (m^2/ha)	Canopy cover (m^2/ha)	Dominant tree species
Temperate							
Natural forest	2200-2350	25-30	Sandy-loam	25 ± 3	56.83	8110	*Alnus nepalensis, Juglans regia, Quercus lamillosa, Michelia lanuginosa*
Plantation	2000-2100	20-25	Sandy-loam	15 ± 2	42.54	3136	*Cryptomeria japonica*
Cardamom agroforestry	1700-1900	25-30	Silty/clay-loam	30 ± 5	48.27	5743	*Alnus nepalensis, Beilschmedia sp., Nyssa sp., Erythrina sp.*
Sub-tropical							
Natural forest	900-1000	20-25	Silty-loam	22 ± 4	57.63	3964	*Schima wallichii, Castanopsis indica, C. tribuloides, Shorea robusta*
Mandarin agroforestry	1100-1200	20-25	Silty-loam	5 ± 0.8	4.57	311	*Citrus reticulata*

are cash crops. Cardamom is a shrub by habit and fruits (capsules) are used as spice/condiment, while mandarin is small and yields mandarin-orange fruits. Cardamom is a shade-loving crop and is grown under tree cover.

A total of five stands comprising three stands in temperate and two stands in subtropical forest and agroforestry systems were selected for investigating the partitioning of incident precipitation through different pathways. The altitudes, slopes, tree heights, basal areas, canopy covers and dominant tree species of stands are given in Table 1. Natural forest in temperate and subtropical zones had the largest basal area, followed by the cardamom agroforestry and temperate plantation forests. Canopy cover was highest in temperate natural forest and lowest in the mandarin agroforestry system (Table 1). Soil texture of different forest and agroforestry types are outlined in Table 1, which is either sandy loam, silty loam or clay loam. The texture of the agricultural field soils were loam, clay and silty clay varying at different physiographic divisions of the watershed.

Material and methods

A drainage map of the Mamlay watershed was prepared using SPOT, PLA and survey of India toposheet on 1:50,000 scale. Land-use area was mapped using satellite imageries (IRS 1A/1B, LISS II, FCC, Band 2 3 4), and verified by primary survey. The land-use was broadly categorized into three groups: (i) forest, (ii) agriculture, and (iii) waste lands. The forest cover was further divided into temperate and subtropical natural forests and plantation forest; agriculture into large cardamom agroforestry, mandarin agroforestry and cropped area without tree canopy, and old fallow land; and waste land (which included landslides, rock outcrops, etc.). Discharge of the stream water was measured at first order streams at Tirikhola, Poolkhola, and Pockcheykhola, and at the third order stream at the outlet of the watershed at Rinjikhola (Figure 1). Discharge was measured monthly and pooled into three seasonal values, summer (March-May), rainy (June-October), and winter (November-February). Sediment concentration was calculated by filtering the sediment from collected water samples.

Overland flow and soil loss were estimated from 18 experimental plots under different land-use during 1994 on six events during rainy season. These were estimated using natural shallow surface runoff channels and artificially delineated plots (Pathak et al. 1983; Singh et al. 1983). The delineated plot size was 2 × 2 m for estimation of overland flow and soil loss, and 3 plots were laid in each type of the land-use practice. These plots were delineated with aluminum sheets (inserted in soil for about 6 cm and remaining 15 cm exposed in air) from all sides to prevent water likely to enter from adjacent areas. The plots were selected with 25-30° slope in all the land-uses as majority of the area in the watershed fall in this slope category. The overland flow and soil loss along the slope were estimated from the collecting tank after each rainfall event. Soil samples were collected from surroundings of each of the delineated plots in replicates (n = 5) up to 30 cm depth and samples were mixed together for a representative composite parent soil. These samples were collected just before the rainy season at the time of plot delineation. The eroded soil was sampled in the form of bed-load sediment and suspended clay material from the collecting tank. The suspended clay material was separated by filtration by Whatman filter paper size 41 from the sample water. The soil for nutrient analyses comprised of both bed-load sediment and suspended clay material for eroded soils. Nutrients were separately estimated in parent soils and extrapolated up to 30 cm depth. Organic carbon of soil was estimated following modified Walkley-Black method (Anderson and Ingram 1989). Total nitrogen was estimated by modified Kjeldahl method (Anderson and Ingram 1989). Total phosphorus was extracted using 0.5N HCl (1 gm of soil in 15 ml 0.5N HCl) and ammonium fluoride after oxidation employing 30% H_2O_2, the solution is filtered, and 5 ml of aliquot is added to 15 ml of 0.8 M H_3BO_3 and 10 ml of 0.1N HCl and then the solution is evaporated to dryness. The residue is taken up in 10 ml of 0.1 N HCl and p determined on 2 ml aliquot by chlorostannous reduced molybdophosphoric blue colour method (Jackson 1967). Organic carbon, total nitrogen, and total phosphorus contents up to 30 cm depth in parent soil were estimated using bulk density, soil volume and nutrient concentration values. Total area of each subdivided land-use in the watershed was calculated, and overland flow and soil loss from each of the land-use were estimated. Nutrient loss through eroded soil was extrapolated for each subdivided land use and the total watershed.

Total incident precipitation was recorded in temperate and subtropical sites. Partitioning of incident precipitation into throughfall, stemflow, canopy interception, floor leachate, floor interception, and biomass incorporation was made. Trees were tagged for stemflow measurement in each of the sites, natural forest, plantation forest, cardamom agroforestry in temperate, and natural forest and mandarin agroforestry in subtropical sites. Stemflow was collected by attaching aluminum collars to five trees of different diameter classes in each stand. Within each plot five throughfall collectors and five floor leachate collectors were established. The floor leachate collectors were covered by 2 mm mesh nylon net on the top on which rested the litter, carefully removed from the bottom of the collectors. Floor leachate collectors were inserted into the soil such that the rim of the container was horizontal and level with the surface of the litter. Throughfall collectors rested on the soil surface such that their upper rims were also horizontal and about 20 cm above the surface. All throughfall and floor leachate collectors were set out in a random pattern and measurements were made at different times during the rainy season. Following each sampling, all throughfall and floor leachate collectors were randomly relocated. This technique is likely to produce more accurate estimates of annual volumes than fixed collectors (Kimmins 1973). Throughfall and floor leachate volumes were calculated considering the width of the upper rim of collecting vessels and converted to mm. Average stemflow volume per tree for each species for a sampling period was calculated. These volumes were then multiplied by number of trees present to obtain the total stemflow volume for each plot and then converted to mm. The biomass incorporation was calculated by using annual biomass increment specific for each stand. The tree density and annual biomass increment values in the present study were used from previous studies done in the same watershed: (i) temperate natural forest and plantation forest (Sundriyal and Sharma 1996), (ii) temperate cardamom agroforestry (Sharma et al. 1994), (iii) subtropical natural forest (Sundriyal et al. 1994a) and (iv) mandarin agroforestry (Sharma et al. 1995). Canopy interception was calculated by subtracting throughfall and stemflow values from incident precipitation. Forest-floor interception was derived from the difference of the forest-floor leachate with the added value of throughfall and stemflow.

Nutrient analyses of precipitation, throughfall, stemflow, and floor leachates were made in different forest and agroforestry sites. The pH of precipitation and partitioned water samples was measured using glass electrode digital pH meter. Estimation of organic-N was made by distillation after digestion whereas for ammonium-N and nitrate-N direct distillation method was followed. Distillation was done using Kjeldahl apparatus and organic-N, ammonium-N and nitrate-N were estimated gravimetrically following Allen

Table 2. Sediment concentration and discharge in three perennial streams and outlet of the Mamlay watershed

Stream	Season	Discharge (l/second)	Sediment concentration (mg/l)
Tirikhola	Summer	11	5.05
	Rainy	242	347.56
	Winter	35	57.32
Poolkhola	Summer	4	2.52
	Rainy	145	387.18
	Winter	42	69.74
Pokcheykhola	Summer	2	0.39
	Rainy	92	128.29
	Winter	32	84.07
Rinjikhola*	Summer	363	4.56
	Rainy	2840	324.74
	Winter	448	83.64
ANOVA P-values† (Rinjikhola values not considered in analysis)			
Stream		0.01	0.01
Season		0.005	0.005
Stream × Season		0.005	0.005
L.S.D.(0.05)		25	49.37

* Watershed outlet
† Beneath each column, P-values associated with an analysis of variance (ANOVA) are given, with L.S.D. values (P=0.05) applicable for means of streams and seasons.

Table 3. Rainfall, overland flow and soil loss during the rainy season in selected sites under different land-use of the Mamlay Watershed

Land-use	Rainfall* (mm)	Overland flow (% of rainfall)	Soil loss (kg/ha)
Forests			
Temperate	1482	2.56	6
Sub-tropical	1222	4.55	137
Agriculture			
Cardamom agroforestry	1482	2.17	30
Mandarin agroforestry	1222	4.76	145
Cropped area	1482	9.55	477
Fallow land	1349	3.77	43
ANOVA P values Land-use	—	0.005	0.005

*Total rainfall during May to October 1994
Values of overland flow and soil loss are mean of six samplings

Table 4. Nutrient concentration (mg/g) of parent and eroded soils under different land-use of the Mamlay watershed

Land-use	Soil type*	Total nitrogen	Organic carbon	Total phosphorus
Forest				
Temperate	PS	8.13	79.98	1.63
	ES	11.25	51.32	1.22
Sub-tropical	PS	2.60	24.09	0.78
	ES	3.92	28.37	0.65
Agriculture				
Cardamom-agroforestry	PS	3.33	23.87	0.75
	ES	13.83	62.16	0.68
Mandarin-agroforestry	PS	2.28	19.54	0.73
	ES	7.39	67.54	0.68
Cropped area	PS	2.33	44.16	1.60
	ES	4.92	24.87	1.42
Fallow land	PS	2.60	44.05	1.77
	ES	9.25	54.04	2.40
ANOVA P values†				
Land-use		0.005	0.005	0.005
Soil type		0.005	N.S.	N.S.
Land-use ´ Soil type		0.005	0.005	N.S.
L.S.D. (0.05)		1.32	11.11	-

*PS = Parent soil; ES = Eroded soil
†Beneath each column P values associated with an analysis of variance (ANOVA) are given, with L.S.D. values (P = 0.05) applicable for means of land-use and soil type. N.S. is not significant
Note: Values are mean (n = 5) composit samples

Table 5. Nutrient content in parent soil and loss through eroded soil under different land-uses of the Mamlay watershed

Land-use	Parent soil (up to 30 cm depth)			Eroded soil		
	Total nitrogen	Organic carbon	Total phosphorus	Total nitrogen	Organic carbon	Total phosphorus
Forests						
Temperate	17.15	168.68	3.44	0.068	0.308	0.007
Sub-tropical	6.51	60.35	1.95	0.537	3.887	0.089
Agriculture						
Cardamom-agroforestry	6.42	46.05	1.45	0.415	1.865	0.020
Mandarin-agroforestry	5.64	48.30	1.80	1.072	9.793	0.099
Cropped area	5.41	102.54	3.72	2.345	11.863	0.677
Fallow land	6.21	105.19	4.23	0.398	2.324	0.103

(1989). Total phosphorus was estimated after evaporation by acidifying and heating the samples and then following molybdophosphoric blue colour method (Allen 1989).

Results

Drainage, discharge, and sediment concentration. Drainage of the Mamlay watershed is classified dendritic and texture is fine in the upper part of the watershed. Outlet for the watershed is the Rinjikhola that feeds the river Rangit, a main tributary of Tista river. The total length of first order stream is 60.60 km, second order stream 12.15 km and third order 9.85 km. The watershed has a total area of 30.14 km^2 and the total stream length is 82.6 km. The drainage density (the total length of streams per unit area) of the watershed is very high having a value of 2.74. Total numbers of channels are 80, 18 and 7 in the first, second and third order streams, respectively. The bifurcation ratio (ratio between the number of streams of a particular order and that of the streams of the next higher order) of the first order stream was 4.44 and the second order stream 1.14.

Discharge was greatest in the rainy season and smallest in the summer (Table 2). The greatest discharge of 2840 l/second was recorded in rainy season and the smallest of 363 l/second in summer season in Rinjikhola. Among different streams the discharge increased from Pockcheykhola < Poolkhola < Tirikhola and the order varied significantly only in rainy season. Sediment concentration varied distinctively with seasons in different streams and the outlet of the watershed (Table 2). In the first order streams the sediment concentration ranged from 0.4 to 5 mg/l in summer, 57- 84 mg/l in winter and 128-387 mg/l in rainy seasons. In Rinjikhola, sediment concentration was minimum (5 mg/l) in summer which increased to 325 mg/l during rainy season (Table 2).

Precipitation, overland flow, and soil loss

Precipitation was recorded at six locations (Figure 1) with different slope and aspects in the watershed covering low, mid and high hills for the period of four years from 1991-1994. The average annual precipitation for the four year period was 2016 mm in high hills (at 1900 m amsl), 1737 mm in mid hills (at 1200 m amsl) and 1460 mm in low hills (at 500 m amsl) of the watershed. In 1994 the precipitation was 1590 mm in high hills, 1434 mm in mid hills, and 1235 mm in low hills. Overland flow (percentage of rainfall during rainy season) was estimated to be largest in cropped area (9.6%) and smallest in cardamom agroforestry (2.2%). Soil loss was greatest in cropped area (477 kg/ha) and smallest in dense mixed temperate natural forest (6 kg/ha, Table 3).

Nutrient concentration in parent soil and eroded soil was estimated during the rainy season in different subdivided land uses and the values are presented in Table 4. Concentrations of nitrogen were higher in eroded soil than the parent soil. Total nitrogen content in the parent soil up to 30 cm depth was highest in temperate forest and very little variation was recorded in other land uses. Organic carbon content was highest in temperate forest followed by fallow land, cropped area, subtropical forest, mandarin agroforestry, and lowest in cardamom agroforestry. Total phosphorus content ranged from 1.45 to 4.23 Mg/ha, highest being recorded in fallow land and lowest in cardamom agroforestry (Table 5). Total nitrogen content was smallest in the eroded soil (0.068 kg/ha) in temperate forest and largest in cropped area (2.345 kg/ha). Similarly largest loss of organic carbon and total phosphorus through soil erosion were recorded in cropped area and smallest from temperate forest (Table 5).

The total area in hectares and per cent coverage of different land uses of the watershed are presented in Table 6. Overland flow, soil loss and nutrient loss through eroded soil from the total area of each land use and the entire watershed were estimated and presented in Table 6. The overland flow was highest from cropped area and lowest from mandarin agroforestry. Total flow from the watershed was 2288 × 10^6 l. Soil loss was 600 ×10^3 kg/year from the watershed and the highest value of 582 × 10^3 kg/year was recorded from the cropped area and the rest 18 × 10^3 kg/year was shared by the remaining land uses. The total nitrogen loss through eroded soil was 3035 kg/year, organic carbon 15438 kg/year and total phosphorus 848 kg/year from the watershed (Table 6).

Precipitation partitioning pathways. Partitioning of incident precipitation into various pathways in natural forest, plantation and cardamom agroforestry in tem-

Table 6. Overland flow, soil and nutrient loss in the watershed under different land uses (values calculated for total area basis under different land uses)

Land-use	Area		Overland flow (x10^6 l)	Soil loss (kg/year)	Nutrient loss through eroded soil (kg/year)		
	ha	%			Total nitrogen	Organic carbon	Total phosphorus
Forest							
Temperate	765	25.38	311	4590	52	236	5
Sub-tropical	21	0.70	14	2877	11	82	2
Agriculture							
Cardamom agroforestry	123	4.08	42	3690	51	229	3
Mandarin agroforestry	19	0.63	13	2755	20	186	2
Cropped area	1220	40.48	1853	581940	2861	14473	826
Fallow land	100	3.32	55	4300	40	232	10
Wasteland	766	25.41	—	—	—	—	—
Total	3014	—	2288	600152	3035	15438	848

Table 7. Partitioning of incident precipitation into various pathways in different land-use at temperate and sub-tropical zones of the Mamlay watershed

Parameters	Temperate			Sub-tropical	
	Natural forest	Plantation forest	Cardamom agroforestry	Natural forest	Mandarin agroforestry
Incident precipitation (mm)	1482	1482	1482	1222	1222
Throughfall (mm)	1190 (210)	488 (63)	816 (92)	708 (37)	752 (83)
Stemflow (mm)	147 (21)	264 (34)	57 (6)	4.9 (0.4)	62 (8)
Canopy interception (mm)	145 (26)	730 (141)	609 (82)	509 (57)	408 (63)
Floor leachate (mm)	644 (80)	619 (175)	608 (222)	277 (87)	595 (119)
Floor interception (mm)	693 (91)	133 (24)	265 (57)	436 (59)	219 (34)
Biomass incorporation (mm)	0.94	0.63	0.53	1.59	0.27

Note: Standard errors are given in parenthesis (n=6)

perate zone, and natural forest and mandarin agroforestry in subtropical zone of the watershed is presented in Table 7. In temperate natural forest precipitation partitioned into 80.3% throughfall, 9.9% stemflow and 9.8% intercepted by canopy. About 48% of the water was collected as leachate and the floor interception was 52% (Table 7). In the case of plantation in temperate forest, 49% of canopy interception was recorded. In the temperate cardamom agroforestry, throughfall was recorded 55% of total precipitation, canopy interception was 41% and stemflow was just 4%. In the subtropical natural forest, throughfall was about 58%, canopy interception was 42% and the stemflow was negligible that amounted less than 1% (Table 7). The floor leachate was 39% and remaining 61% was recorded to be the floor interception. Stemflow in the mandarin agroforestry system was higher (5%) than that recorded from sub-tropical natural forest. The total amount of water on the floor partitioned as 73% leachate and remaining 27% as floor interception in the mandarin agroforestry system (Table 7).

The pH and nutrient analyses in precipitation water, throughfall, stemflow, and floor leachate were estimated in different forest and agroforestry stands in subtropical and temperate zones of the watershed (Table 8). The pH of water in precipitation of temperate zone was towards neutral while it was acidic at the subtropical site. Ammonium concentration was almost the same in both the sites, while nitrate concentration was nearly two times higher in precipitation of subtropical site (Table 8). The pH of throughfall and stemflow of plantation forest in temperate site was acidic. The stemflow was also acidic in the subtropical natural forest. Ammonium-N concentration in throughfall was highest in natural forest while nitrate-N was highest in plantation forest at temperate site. In stemflow water both ammonium-N and nitrate-N were very high in plantation forest in the temperate zone. Nitrate-N was high in natural forest at the subtropical site. Floor leachate pH in cardamom agroforestry was lower than natural and plantation forests of temperate sites. Total-P in floor leachate was recorded highest in subtropical natural forest and lowest in cardamom agroforestry.

Table 8. pH and nutrients in precipitation, throughfall, stemflow and floor leachate in different forest/agroforestry sites in the Mamlay watershed

Parameter	Temperate			Sub-tropical	
	Natural forest	Plantation forest	Cardamom agroforestry	Natural forest	Mandarin agroforestry
Precipitation*(n=5)					
pH	6.67 ± 0.59			5.61 ± 1.19	
NH_4^+(mg/l)	1.81 ± 0.23			1.87 ± 0.47	
NO_3^-(mg/l)	2.73 ± 0.42			5.33 ± 0.76	
Throughfall (n=9)					
pH	6.61 ± 0.19	5.80 ± 0.28	6.36 ± 0.16	6.01 ± 0.27	6.49 ± 0.44
NH_4^+(mg/l)	2.83 ± 0.42	2.48 ± 0.38	2.71 ± 0.30	2.13 ± 0.51	1.45 ± 0.34
NO_3^-(mg/l)	5.73 ± 1.68	7.81 ± 2.14	6.45 ± 1.72	5.91 ± 0.96	5.25 ± 0.72
Organic-N (mg/l)	0.84 ± 0.08	0.78 ± 0.16	0.88 ± 0.10	0.96 ± 0.07	1.24 ± 0.23
Total-P (mg/l)	0.81 ± 0.19	0.92 ± 0.17	0.92 ± 0.23	0.99 ± 0.20	0.44 ± 0.02
Stemflow (n=9)					
pH	6.93 ± 0.25	5.60 ± 0.42	6.42 ± 0.17	5.88 ± 0.25	6.36 ± 0.49
NH_4^+(mg/l)	3.76 ± 0.63	6.92 ± 1.45	2.64 ± 0.42	3.78 ± 0.64	2.78 ± 0.38
NO_3^- (mg/l)	7.23 ± 1.65	7.64 ± 2.38	5.79 ± 2.78	9.04 ± 2.51	3.96 ± 0.82
Organic-N (mg/l)	1.54 ± 0.15	1.13 ± 0.15	0.83 ± 0.10	1.31 ± 0.14	1.36 ± 0.13
Total-P (mg/l)	0.84 ± 0.16	0.53 ± 0.18	0.40 ± 0.09	0.93 ± 0.21	0.58 ± 0.09
Floor leachate (n=6)					
pH	6.57 ± 0.21	6.68 ± 0.27	6.10 ± 0.34	6.57 ± 0.31	5.98 ± 0.27
Organic-N (mg/l)	1.26 ± 0.12	0.96 ± 0.16	1.60 ± 0.27	1.47 ± 0.13	1.43 ± 0.23
Total-P (mg/l)	1.03 ± 0.29	1.10 ± 0.16	0.60 ± 0.17	1.60 ± 0.28	0.96 ± 0.12

*Precipitation was measured at one site each in temperate and sub-tropical zone and not on land-use basis

Discussion

The drainage texture is fine on the higher elevation and gradually becomes coarse at the valley. Fine drainage texture is vulnerable for high rates of erosion under extensive cultivation. In the Mamlay watershed all high hill areas are located under forest cover where fine drainage texture is prevalent experiencing minimum soil erosion. Because of the fine texture and dense forest this zone has high underground water potential. In spite of coarse drainage texture, erosion was greatest in the middle hills because of dense population and extensive cultivation. The discharge in various streams showed high seasonality and direct relationship with precipitation. About 90% of annual precipitation was received in the monsoon and the discharge was highest in this period. Many streams dried completely in the summer season mainly in the mid hills because of deforestation and extensive human activities. This belt is located between two major thrusts of the watershed where water percolates from upper thrust and appears in the lower thrust through sub-surface flow. Sediment concentration also showed seasonality similar to discharge. The sediment concentration in different seasons at all streams showed direct relationship with precipitation. The highest sediment concentration in rainy season was attributed to (i) high rainfall during this period, (ii) steep slopes, and (iii) extensive cultivation of the soil practice in this season.

Rainfall was distributed seasonally and

more than 90% of the input was received during May to October. The year 1994 received about 20% less rainfall compared to the average of the four years 1991-1994. The overland flow in the cropped area was highest because of intensive cultivation and steep aspect of the land. Soil loss of 477 kg/ha/year from agricultural land represents removal of about 1 mm depth, soil in about 20 years. A survey of agricultural fields on unterraced slopes showed more than 60% pebbles/stones (Sharma et al. 1992). Participatory inventory with farmers also revealed high soil erosion problem and the indicators as observed by farmers were exposure of red soil and stones of deeper soil profile. The overland flow decreased in mandarin agroforestry as a result of protection by trees. In the subtropical forest relatively high amount of overland flow were recorded because of high biotic pressure. Prior to the year of experimentation this forest was burned which destroyed the ground and understorey species. This would contribute to greater overland flow and soil loss. Overland flow and soil loss from the fallow land was low compared to agricultural land as it was not disturbed and was covered by ground vegetation. Similar observations on fallow lands were also made in shifting agriculture system in north-eastern India by Toky and Ramakrishnan (1981). Temperate forest showed relatively lower overland flow and soil loss. In the central Himalaya, comparatively less overland flow was recorded from the temperate forest but the soil loss was more than the temperate forest of the present study (Singh et al. 1983). The high overland flow in the present study located in the eastern Himalaya was the consequence of higher rain intensity and more annual precipitation. In spite of more overland flow in the temperate natural forest in the present study soil loss was less than the central Himalaya because of complete ground vegetation, thicker forest floor litter and more stratification of the forest. Cardamom agroforestry is a traditional practice of the region and is regarded to be profitable and sustainable farming system. The overland flow in the cardamom agroforestry was minimum because of good canopy coverage and high density of trees. The less overland flow values in temperate natural forest and cardamom agroforestry indicate that the catchment areas under these land uses encourage high infiltration and subsurface flow. Bren and Turner (1979) and Bren (1980) studied the surface runoff on steep forested infiltrating slopes in Australia and reported that overland flow was very low (0.005% of the rainfall). The hydrological response of a forested hill slope to rain is often dominated by the lateral down slope movement of water within the soil system. Overland flow may be a rare occurrence on such forested watershed.

The cropped area occupies 54% of the total watershed area excluding other usage such as landslides and rock outcrops. From this 54% area of agriculture land the overland flow was 81%, soil loss 97%, total-N loss through soil erosion 94%, organic-C 94%, and total-P 97% with respect to total watershed loss. Soil and nutrient losses from this land use were more than 94% of total watershed indicating that agriculture practice without agroforestry in such unterraced sloping land and in high rainfall areas are highly vulnerable. Therefore, strong agroforestry based agriculture such as mandarin, cardamom and horti-agri-silvi-system is recommended in the watershed for conservation of soil, water and nutrients in such a fragile upland farming system.

Nitrogen and organic carbon contents were high in temperate forest as a result of humus accumulation and higher organic matter input. The organic carbon of the cropped area and fallow land was also high which has resulted from application of organic manure in the system. Nutrient loss could be more in the cropped area because of the high soil loss. The nutrient concentration in eroded soil in mandarin agroforestry was high but relatively little soil erosion was recorded. The higher loss of nutrient through soil erosion in the subtropical forest compared to temperate forest is mainly attributed to higher soil loss in the subtropical forest. Relationship between soil loss and nitrogen loss ($r = 0.974$, d.f. = 20, $p < 0.001$), soil loss and organic carbon loss ($r = 0.956$, d.f. = 20, $p < 0.001$), and soil loss and total phosphorus ($r = 0.918$, d.f. = 20, $p < 0.001$) were positively significant. The ranking of land use vulnerable to soil erosion with respect to loss of total-N and total-P was cropped area > mandarin agroforestry > subtropical forest > fallow land > cardamom agroforestry > temperate natural forest.

The throughfall, stemflow, and canopy interception results are similar to that of forests of the central Himalaya (Pathak et al. 1983). Higher throughfall in the temperate natural forest than the plantation forest was because of broad leaf nature and more canopy coverage of natural forest species than the coniferous *Cryptomeria japonica* plantation. Stemflow was more in the plantation forest because of conical canopy architecture of *Cryptomeria* and stream lining of water through stemflow. Our data on canopy interception corroborate that broad-leaved forest intercepts less rainfall than do coniferous species. Pathak et al. (1983) reported positive relationship of interception with canopy cover in the oak forest of the central Himalaya. Waring et al. (1980) argued that the surface area of the forest is an important determinant in interception processes. Floor interception of precipitation was directly related with the floor litter composition and quantity. Broad-leaved litter composition showed higher floor interception and relatively smaller floor leachate. Precipitation partitioning was studied only in systems where there was tree cover. Comparison between forest types and agroforestry systems showed that totality of canopy and floor interception is very important determinant for water availability with respect to floor leachate. Forests showed more floor interception as a result of thicker litter layer. Mandarin agroforestry have smaller floor interception and showed fairly high soil erosion indicating inverse relationship. Biomass incorporation of water indirectly shows the annual production of stands. The subtropical natural forest was the most productive and the mandarin agroforestry the least in terms of living biomass incorporation of water (woody biomass productivity of subtropical natural forest 17.83 t/ha/year; large cardamom agroforestry 10.8 t/ha/year; temperate natural forest 8.32 t/ha/year; and mandarin agroforestry 3.6 t/ha/year were reported by Sharma et al 1994, 1995; Sundriyal and Sharma 1996; and Sundriyal et al 1994). This is a measure of mainly the production of perennial parts which is accounted in terms of living biomass incorporation.

In the partitioning of precipitation the nutrients on the leaf surface, stem bark, and floor litter are mobilized. Our study shows different levels of mobility of nutrients in different pathways of partitioning. Precipitation also contributed ammonium-N and nitrate-N, and the values were different for temperate and subtropical zones. Total-P loss through floor leachate was highest in subtropical natural forest as a consequence of fire in the preceding winter of the experimentation. Organic-N loss was almost similar from different land uses except for temperate plantation forest that showed relatively lower value. This may be because of slow decomposition of conifer needles on the floor in plantation forest.

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Conclusion

The Mamlay watershed presents a major human habitation zone in the eastern Himalayas. All the land uses and cultivation practices followed in the region are found there. A major proportion of the land cover is rainfed agriculture involving intensive cropping practices on open, unterraced slopes, and agroforestry systems. The study was objectively divided into three sets of components of hydrological cycle, (i) stream flow and sediment concentration, (ii) overland flow and concomitant soil loss rates under different types of land management, and (iii) precipitation namely throughfall, stemflow, canopy interception, floor leachate, floor interception and biomass incorporation pathways in forests and agroforestry systems. The catchment draining into a particular stream in the watershed comprised of six land use practices and there was no uniform land use for a stream.

The sediment load was greatest in rainy season in all the streams of the watershed. This was attributed to high rainfall, steep aspects and extensive cultivation practices in the rainy season. The overland flow, and soil and nutrient loss were greatest from open agricultural fields and least in cardamom agroforestry. The values in mandarin agroforestry were also much smaller than those from the open agricultural area. This suggests an increase of agroforestry systems from the existing open agricultural (cropped) practice. Such a practice would help in soil and nutrient conservation consequently enhancing the soil fertility status and productivity. The results for the overland flow, soil and nutrient loss, and precipitation partitioning in different pathways in natural forest and agroforestry systems suggests that these land uses promote conservation of soil, water and nutrients. Sequential precipitation partitioning in forests and agroforestry systems depend on systems' vertical stratification. An inverse relationship was observed between floor interception and soil erosion. Therefore, it is recommended that the dense mixed forest cover should be maintained at higher elevations in the watershed to regulate and ensure stream flow and also to minimize the risks of landslides. The conversion of forests to agricultural land has been quite conspicuous in the last few decades (this is a general trend in most of the areas in the Himalaya) and it has to be reversed immediately.

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